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Research Article

Carbon Footprint in Paddy Production: A Study on Farmers in Khulna District, Bangladesh

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Abstract

Paddy production is essential for food security but is also an important source of greenhouse gas emissions, particularly methane and nitrous oxide. This study estimates the carbon footprint of paddy production and identifies its key determinants among farmers in Khulna District, Bangladesh, with particular attention to farming systems, irrigation, crop-residue management, training and CSA adoption. Primary data were collected through face-to-face interviews with 200 paddy farmers selected using a multi-stage sampling procedure from four villages in Dacope and Batiaghata upazilas during September–October 2024. Greenhouse gas emissions were converted into carbon-dioxide equivalents using established emission factors and global-warming potentials. Descriptive statistics, an independent-samples t-test and ordinary least squares regression were used to assess emission patterns and determinants. Diesel-powered irrigation increased the carbon footprint by 3.35 CO_2-eq units, whereas rain-fed irrigation reduced it by 5.23 units. CSA tools reduced emissions by 12.29 units. Composting and soil incorporation of crop residues reduced emissions by 10.33 and 9.19 units, respectively, compared with residue burning. Modern and mixed farming systems reduced emissions by 6.25 and 8.31 units, respectively, relative to traditional farming. The model explained 48.02% of the variation in carbon footprint. The findings indicate that cleaner irrigation, CSA technologies and sustainable residue management can reduce emissions without undermining paddy production. The study links farm-level carbon-footprint estimates with socioeconomic and management factors in a climate-vulnerable coastal setting. It provides locally grounded evidence for policies promoting farmer training, improved water management, cleaner energy and low-emission residue practices in Bangladesh's rice sector.

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I. INTRODUCTION

Paddy is a primary staple food for a large share of the world's population, and most rice is produced in Asia (IRRI, 2023). Rice production is also an important source of agricultural greenhouse gas emissions, particularly methane and nitrous oxide (Linquist *et al*., 2012). A carbon footprint expresses greenhouse-gas emissions associated with an activity or product in carbon-dioxide-equivalent terms. In paddy production, this includes emissions associated with inputs, on-farm cultivation, harvesting and post-harvest activities (Miao *et al*., 2023). Paddy production can be a major contributor to GHG emissions, primarily CH_4 and N_2O (Linquist *et al*., 2012).

Paddy production contributes substantially to agricultural CH_4 emissions globally (Neue, 1997). Khulna District is a well-known rice-growing area in southwest Bangladesh. Three main rice seasons, Aus (summer), Aman (monsoon), and Boro (winter), support year-round rice cultivation in the region. Paddy production is important for local food security and farm livelihoods. This raises concerns about the specific carbon footprint of rice production in Khulna, which remains understudied. These emissions arise from various agricultural practices, including the decomposition of organic matter, fertilizer application, and the burning of agricultural residue. Paddy fields harbour diverse microbial communities that decompose organic matter after harvest, releasing CH_4 as a byproduct (Neue, 1997). Excessive use of nitrogenous fertilizers in rice cultivation can contribute to N_2O emissions from agricultural soils (Liu *et al*., 2010).

Burning crop residues releases greenhouse gases and other air pollutants; accordingly, the IPCC provides default emission factors for residue burning (IPCC, 2006). According to the IPCC Fourth Assessment Report, the 100-

year global warming potential of CH_4 is 25 times that of CO_2 (IPCC, 2007). Agricultural activities are responsible for a substantial share of anthropogenic CH_4 emissions, and rice cultivation is an important agricultural methane source (Scheehle & Kruger, 2006; USEPA, 2006). The study region is also vulnerable to climate-related stresses, which adds another layer of complexity. Warmer conditions can enhance processes associated with methane production in flooded rice soils (Neue, 1997).

The study provides a quantified assessment of the carbon footprint of paddy production and identifies key emission factors. Based on the identified factors, this research will inform the development of targeted mitigation strategies, such as improved water management, optimized fertilizer application, and alternative residue management. It will also encourage the adoption of sustainable practices such as introducing low-nitrogen rice varieties and promoting residue incorporation for soil health. Ultimately, this study will contribute to developing a sustainable rice production system in Khulna, ensuring food security for future generations while minimizing environmental impact. However, all the determinants are location- and context-specific (Kamruzzaman, 2015).

Therefore, it is necessary to evaluate how paddy farming relates to climate change through increases in the carbon footprint. From a social science perspective, this study evaluates the importance of addressing the carbon footprint of paddy farming in Khulna to balance food security with environmental sustainability. The rest of this paper presents the methods and materials, including study locations, data collection and sampling techniques, and analytical approaches in Section II; results and discussion in Section III; and conclusion and policy implications in Section IV. This study aims to identify the key determinants influencing the carbon footprint of paddy farming, with a focus on analysing how different farming practices contribute to carbon emissions in Khulna District. The researcher specifically examines those determinants in the context of paddy farming and provides insights into the environmental impact of local agricultural methods.

II. MATERIALS AND METHODS

A. Study Location

This research selected the study area based on one criterion: high paddy production. The cultivation of Boro paddy has been reported to be advancing rapidly in the Khulna agricultural region (BSS, 2024). Agriculture in this region is mainly dominated by paddy.

Thus, the study was conducted in 2 of the 10 upazilas of Khulna District: Dacope and Batiaghata. Dacope is a region where land ownership influences how farmers manage their land and resources, affecting their carbon footprint. On the other hand, Batiaghata is a region where paddy production in flooded fields releases methane, a potent greenhouse gas. This is an area beside the river, where more rainfall may result in higher methane emissions from paddy production. Therefore, these two areas were selected for this study. Samples were taken from 2 unions in the selected upazilas. The unions were Bajua of Dacope and Batiaghata Union of Batiaghata Upazila. Then, from each union, two villages were selected randomly.

B. Data Collection and Sampling Technique

The study primarily relied on primary data. Data were gathered via in-person interviews. Therefore, it was crucial to create a well-organized and reliable questionnaire. Initially, a questionnaire was prepared. The preliminary questionnaire underwent a pilot survey with 10 respondents from each upazila for pretesting purposes. The final version of the questionnaire was refined by eliminating extraneous questions and incorporating necessary questions adjusted based on the pilot survey.

The author employed a multi-stage sampling technique to choose a representative sample from the designated study area. Khulna District was conveniently chosen as the primary study region during the first phase. In the second phase, Batiaghata and Dacope upazilas were purposefully selected because they are known for paddy production. During the third stage, a random selection was made among the eight villages in Bajua and eighteen villages in Batiaghata Union, resulting in two unions being selected. In the fourth phase, two villages from each union were selected randomly. During the last phase, 200 farmers from these 4 villages were randomly selected and surveyed using a random sampling procedure. The survey population consisted solely of paddy farmers. Subsequently, the total number of paddy farmers was collected from the Agricultural Extension Office.

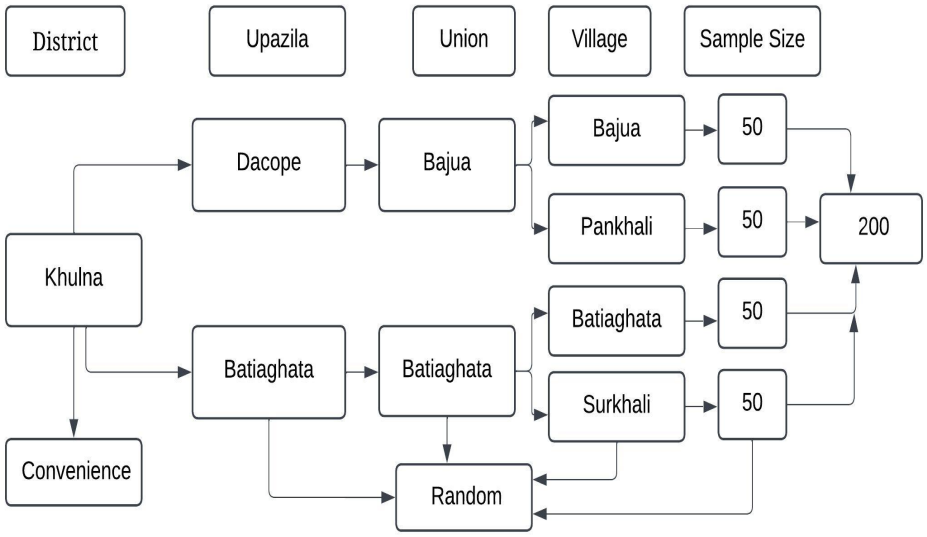


Fig.1 Sampling Framework
Source: Author's compilation based on field survey, 2024

The sample size was then calculated using a proportionate random sampling equation (Naing *et al*., 2006), which is given below.

$$n = \frac{NZ^2P(1-P)}{ND^2 + Z^2P(1-P)} \dots\dots\dots\dots\dots (1)$$

Here, n = Sample size
N = Population (Total number of farmers)
Z = Confidence level (at 95 percent level, Z=1.96)
P = Estimated population proportion (0.5, which maximizes the sample size)
D = Error limit of 10 percent (i.e., 0.1).

The above formula, adapted from Naing *et al*. (2006), was used to estimate the minimum sample size required for the study. Although the required sample size was calculated using the above equation, approximately 200 respondents met the study requirements. We could not go beyond 200 respondents due to budget constraints. Data were collected from September to October 2024.

C. *Variables of the Study*

Different types of explanatory variables were used in the study. The major outcome variable is carbon footprint, measured by kg CO_2-eq/bigha.
Empirical Analysis

D. Carbon Footprint Estimation

The carbon footprint of paddy production was calculated by breaking the production process into various emission tiers in accordance with the framework proposed by Pandey and Agrawal (2014). Agricultural emission sources consisted of field operations, energy consumption, and the production of inputs. Thus, the total GHGs were determined by accounting for both direct and indirect GHG sources.

Tier 1 contains direct on-farm emissions, such as those resulting from soil processes, machinery operation, and crop management activities. Tier 2 includes indirect emissions connected to energy consumption, especially electricity. Tier 3 includes emissions associated with the production, transport, and distribution of agricultural inputs such as fertilizers, pesticides, and machinery.

The GWPs for each tier were computed according to Pandey and Agrawal (2014):

GWP of tier (kg CO_2-eq/bigha) = (CH_4 emission/removal × 25) + (N_2O emission/removal × 298) + (CO_2 emission/removal) ..... (2)

The individual GWP values were then added together to get a total estimate of the GWP, as follows:

GHG Emission Coefficient = Σ (GWP of all tiers).....(3)

GWP is the global warming potential of GHGs in units of carbon dioxide equivalent (CO_2-eq). Conversion factors for methane and nitrous oxide were taken from the IPCC global warming potentials adopted by Pandey and Agrawal (2014). The carbon footprint of paddy production was then calculated using the method suggested by Lal (2004). Therefore, the carbon footprint can be determined as follows: Agricultural inputs include fertilizers, fuel, electricity, and other production inputs; grain yield is the overall rice production per unit area. This method allows calculation of the emissions per unit of agricultural production (Lal, 2004). Carbon footprint from agriculture is calculated by the following formula (Lal 2004).

Carbon footprint = Σ (Agricultural input ∗ GHG emission coefficients)/ (Grain yield) …. (4)

E. Methane Emissions from Paddy Cultivation

The factors affecting methane emissions from rice cultivation are water management practices, cultivation period, soil properties, and the application of organic matter. Annual methane emissions were estimated following the methodology recommended in the IPCC Guidelines for National Greenhouse Gas Inventories (Eggleston *et al*., 2006; IPCC, 2006), using the equation shown below:

$$CH_4Rice = \Sigma (EF \times t \times A) \text{ ..... } (5)$$

Where:
CH_4Rice = Methane emission from rice field (kg CH_4 $year^{-1}$)
EF = Daily methane emission factor (kg CH_4 $bigha^{-1}$ day^{-1})
t = Cultivation period of rice (days)
A = Area of rice harvested annually (bigha year-1)

The daily emission factor was modified using scaling factors that take local cultivation conditions into account, as pointed out by Eggleston *et al*. (2006) and IPCC (2006). The emission factor was adjusted according to Equation (6).

$$EF = SFw \times SFpj \times SFo \text{ ..... } (6)$$

Where:
SFw = Scaling factor for water regime in cultivation
SFpj = Scaling factor for pre-season water management.
SFo = Scaling factor for organic amendment to the field.

The default values and adjustment coefficients were taken from the IPCC (2006) Guidelines for National Greenhouse Gas Inventories.

F. Greenhouse Gases from Residue Burning

TABLE I EMISSION VALUES FOR RESIDUAL BURNING

Name of gases	Gef (g kg-1dm)
CO_2	1185
CO	113.2
CH_4	2.7
N_2O	0.07
Nox	3.1
$PM_{2.5}$	27.63
PM_{10}	13
Black carbon	0.69

Source: IPCC, 2006. The data come from IPCC (2006).

The emission factors for crop residue burning were estimated using the default emission factors in the 2006 IPCC Guidelines. The emission factors of major GHGs from rice straw burning are shown in Table I. The above values were applied to estimate emissions from post-harvest residue management practices.

G. Emissions from Fertilizer Application

The emissions of N_2O from agricultural soils were estimated based on the empirical model developed by Bouwman (1996). The emission rate was determined from Equation (7):

$$E = 1 + 0.0125F \text{ ..... } (7)$$

Where:
E = N_2O emission rate (kg N_2O-N $bigha^{-1}$)
F = Nitrogen fertilizer application rate (kg N $bigha^{-1}$ $year^{-1}$)
This model is widely used in agricultural emission studies (Bouwman, 1996) and assumes that more nitrogen fertilizer applied to the field results in more nitrous oxide emissions.

H. Emissions Generated by Fuel Consumption

The estimated emissions from fuel use in farming activities were calculated using the methodology suggested by Al-Gezawe *et al*. (2021). The emissions due to fuel use were determined using Equation (8).

$$FC = [f\ (1/3600)\ PE \times LCV \times 427 \times \eta thb \times \eta m \times (1/75) \times (1/1.36)] \text{ ..... } (8)$$

Where:
The "fuel consumption-related emissions" refer to emissions from fuel consumption.
f = Fuel consumption rate (L h^{-1})
PE = Fuel density (kg L^{-1})
HCV = Higher calorific value of fuel
ηthb = Thermal efficiency of the engine
ηm = Mechanical efficiency of the engine

To maintain consistency in estimating fuel-related emissions, all values of the parameters and conversion coefficients were taken from Al-Gezawe *et al*. (2021).

I. Econometric Estimation

An ordinary least squares (OLS) regression model was used to determine factors influencing the carbon footprint of paddy production. The OLS specification was modified from the specifications of Gujarati and Porter (2009) and Majid *et al*. (2018) and is given as follows.

$$Y = \beta_0 + \beta_1X_1 + \beta_2X_2 + \beta_3X_3 + \beta_4X_4 + \beta_5X_5 + \beta_6X_6 + \beta_7X_7 + \beta_8X_8 + \beta_9X_9 + \beta_{10}X_{10} + \varepsilon i \text{ ..... } (9)$$

Where:
Y = Carbon footprint
β_0 = Intercept term
β_1–β_{10} = Coefficients of explanatory variables
εi = Random error term

Socioeconomic, technological, and management-related factors were used to quantify their influence on carbon emissions from paddy farming using an OLS model.

Further, path analysis was conducted for statistically significant variables, and the direct effects were visualized and analysed.

III. RESULTS

A. Demographic Profile

This section discusses the empirical results of the study and explores the linkages between farming practices, socioeconomic attributes, productivity, and carbon emissions in paddy cultivation. It examines the demographic and economic profile of farmers, land ownership patterns, and the adoption of climate-smart agricultural (CSA) practices. The section also discusses the productivity, cost, revenue, and profitability of traditional, modern, and mixed farming systems. Furthermore, it explores the factors affecting the carbon footprint, focusing on irrigation techniques, residue management, and the implementation of climate-smart technologies. The results support an understanding of the opportunities and limitations of sustainable agriculture and provide evidence-based recommendations to improve low-carbon and climate-resilient paddy production in the study area.

TABLE II SUMMARY STATISTICS

Variable	Unit of measurement	Avg.	Freq.	Percent	Min.	Max.
Age	Years	49.99	-	-	30	70
Education	Years of schooling	6.075	-	-	0	16
Income	BDT/Month	19585.24	-	-	1020	82557.5
Expenditure	BDT/Month	15565	-	-	5000	30000
Household size	Numbers	4.64	-	-	2	7
Household condition	Kacha	-	55	27.50	-	-
	Semi-pucca	-	110	55.00	-	-
	Pucca	-	35	17.50	-	-
Total cultivated Land	Bigha	12.22	-	-	1	48
Farm purpose	Livelihood	-	35	17.50	-	-
	Commercial	-	34	17.00	-	-
	Both	-	131	65.50	-	-
Farming experience	Years	24.59	-	-	5	50
Farming method	Traditional	-	9	4.50	-	-
	Modern	-	155	77.50	-	-
	Both	-	36	18.00	-	-
Method of irrigation	Electronic pumping	-	27	13.50	-	-
	Diesel	-	48	24.00	-	-
	None	-	118	59.00	-	-
	Both	-	7	3.50	-	-
Fertilizer	Chemical	-	96	48.00	-	-
	Organic	-	0	0.00	-	-
	Both	-	104	52.00	-	-
Total production	KG	3666	-	-	300	14400
Revenue	BDT	78250.45	-	-	-5565	330230
Residual management	Burning	-	6	3.00	-	-
	Composting	-	33	16.50	-	-
	Incorporation	-	154	77.00	-	-
	Pulling	-	7	3.50	-	-
Carbon footprint	Kg $CO_{2\ eq}$/bigha	38.38	-	-	22.61	109.49

Source: Author's compilation based on field survey, 2024
[Note: Avg = Average, Freq = Frequency, Min = Minimum, Max = Maximum. *All numbers have been rounded to two decimal places.]

Table II presents the sociodemographic profile of the respondents. The farming population is predominantly middle-aged to older, with an average age of nearly 50 years, ranging between 30 and 70 years. Education levels among respondents are relatively low, with an average of just over 6 years of schooling, ranging from no formal education to 16 years. Household income and expenditure reveal notable economic variability. The average monthly income is approximately 19,585 BDT, while expenditures account for a significant proportion of this, averaging around 15,565 BDT. Income levels vary widely, from as low as 1,020 BDT to over 82,000 BDT, reflecting disparities in economic conditions among farming households. The average household has nearly 5 members, ranging from small families with 2 members to larger ones with 7. Most households reside in semi-pucca structures, indicating a moderate standard of living, while a smaller proportion live in kacha and pucca homes.

In terms of agriculture, the average landholding is about 12 bighas, ranging from as little as one bigha to as much as 48. Nearly two-thirds engage in farming for both livelihood and commercial purposes, while smaller groups focus solely on livelihood or commercial farming. Farmers have considerable experience, averaging almost twenty-five years, which likely influences their reliance on traditional practices despite familiarity with modern methods. Modern farming techniques are widely adopted, with most farmers using them exclusively. Irrigation remains a challenge, as most farmers do not use any irrigation system and rely on rainfall. Of those who do irrigate, most use diesel pumps, while smaller groups rely on electronic pumping or a combination of methods. More than half of the farmers use both chemical and organic fertilizers, while the rest rely entirely on chemical options. No farmers reported using organic fertilizers exclusively, indicating a potential area for promoting sustainable practices.

Production levels average 3,666 kilograms, with significant variability from 300 kilograms to over 14,000 kilograms, suggesting differences in productivity, farm size, or crop type. Revenues also vary greatly, averaging 78,250 BDT, with some farms reporting losses while others generate high returns. Residue management practices are largely sustainable, as most farmers incorporate residues back into the soil. A smaller group uses composting, while only a minority engages in environmentally harmful practices such as burning. The carbon footprint averages around 38 kilograms of CO_2 equivalent per bigha, with values ranging from 22 to over 109 kilograms, indicating a moderate environmental impact that could be reduced through further adoption of sustainable practices.

B. Farm Characteristics

Figure 2 illustrates the distribution of land ownership and management practices among farmers in the study area.

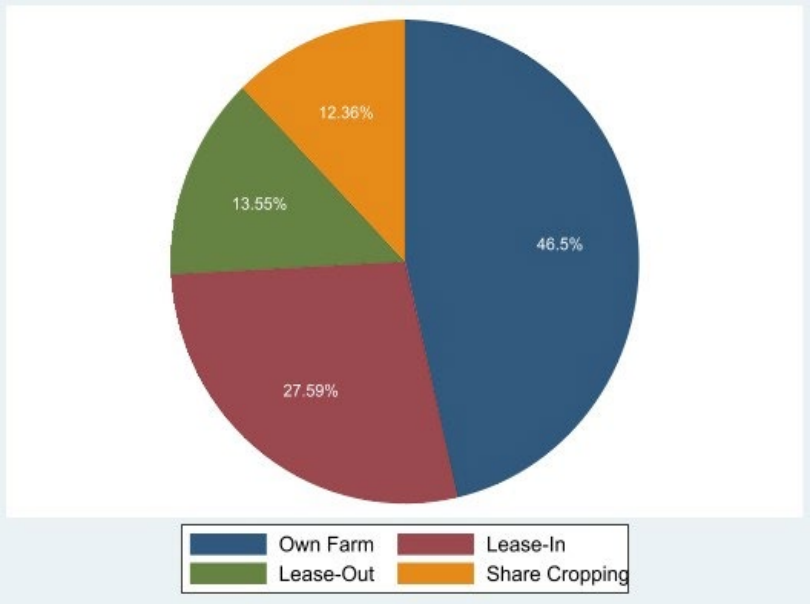


Fig.2 Land Ownership Pattern
Source: Author's Compilation Based on Field Survey, 2024

Figure 2 indicates that owning land for cultivation is the most prevalent practice among farmers in the region. The pie chart shows that a significant portion of farmers are independent landowners. Lease-in is less common. It represents land that farmers lease from others for cultivation, indicating that some farmers rely on leasing land to expand their farming operations. Lease-out is the smallest category. It represents land that farmers lease out to others, suggesting that a small number of farmers have excess land that they lease to other farmers. Sharecropping is also relatively uncommon. It depicts land cultivated under a sharecropping arrangement, where farmers share the produce with the landowner. Thus, sharecropping is less common than owning or leasing land.

TABLE III METHOD OF IRRIGATION AND FARMING METHOD

Method of irrigation	Farming method			
	Traditional	Modernized	Both	Total
Electronic pumping	3	20	4	27
Diesel	2	45	1	48
None	3	90	25	118
Both	1	0	6	7
Total	9	155	36	200

Source: Author's compilation based on field survey, 2024

Table III shows a clear preference for specific irrigation methods depending on the farming approach. The field survey conducted in 2024 reveals a predominant trend toward modernized farming methods across all types of irrigation systems. Of 200 farmers, 118 were not using any irrigation system. Interestingly, 90 of these farmers adopted modernized farming practices. In addition, 25 farmers adopted both modern and traditional farming methods, and a very small proportion relied solely on the traditional farming method.

The diesel-based irrigation system is the second most popular in the region and is used by 48 of the 200 farmers. Among them, 45 farmers use modernized farming methods, indicating a strong association between diesel-based irrigation and modernized methods. Electronic pumping is employed by 27 farmers, showing a similar trend; 20 farmers adopted modernized farming methods, while only 3 use traditional methods and 4 use both methods.

Overall, the distribution highlights a clear dominance of modernized farming practices, especially in non-irrigated settings, indicating that technological advancement is widely embraced irrespective of irrigation methods. The low prevalence of traditional farming, with only 9 farmers across all irrigation categories, indicates a shift away from traditional methods, likely driven by the efficiency and productivity gains offered by modern techniques.

C. Utilizing the Practice of CSA Techniques

Figure 3 illustrates that the adoption of CSA techniques plays a crucial role in enhancing agricultural resilience to climate change while improving productivity and sustainability.

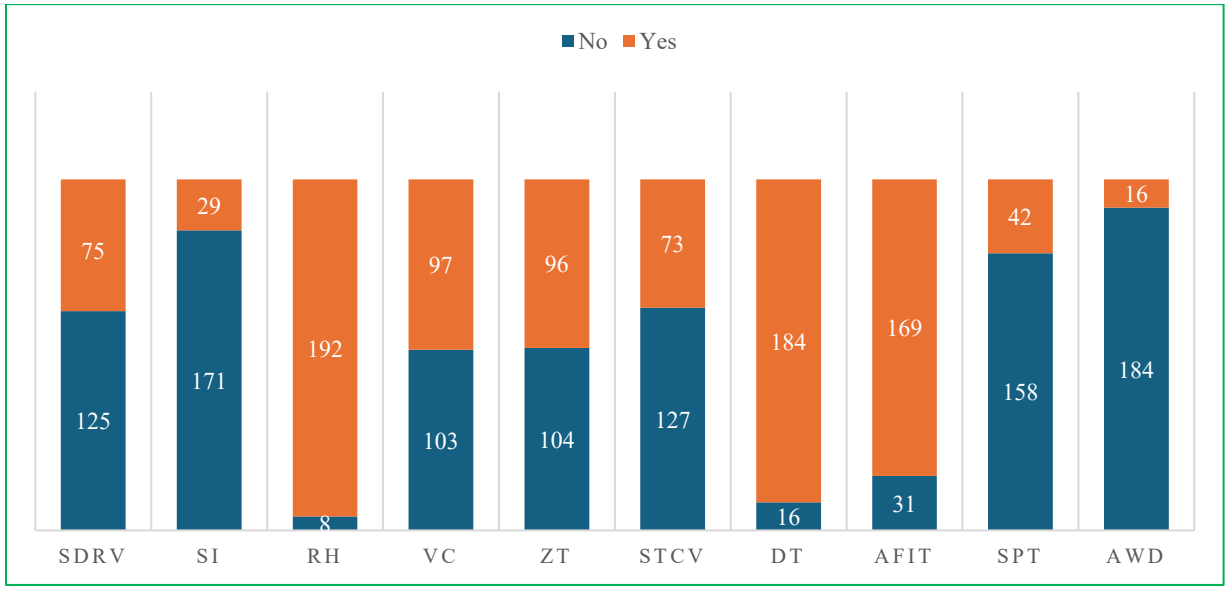


Fig.3 CSA practices
Source: Author's compilation based on field survey, 2024
[Note: Short-duration rice varieties= SDRV, Solar irrigation= SI, Rainwater harvesting= RH, Vermicompost= VC, Zero Tillage= ZT, Salt-tolerant crop varieties= STCV, Double transplanting= DT, Alternate furrow irrigation technology= AFIT, Shifting planting time= SPT, Alternative wetting and drying= AWD]

Figure 3 illustrates the adoption and non-adoption of different climate-smart agriculture (CSA) practices among farmers. Among 200 farmers, 75 adopted short-duration rice varieties and 125 did not use them. Only 29 farmers adopted solar irrigation practices, and most farmers (171) were non-adopters. Rainwater harvesting (RH) is the most common CSA practice; almost all farmers (192) use it, and only a few (8) do not. Vermicompost (VC) and zero tillage (ZT) show relatively balanced adoption patterns. Vermicompost is adopted by 97 farmers, while 103 farmers do not adopt it.

Similarly, zero tillage (ZT) is adopted by 96 farmers, while 104 farmers do not adopt ZT. Seventy-three farmers adopted salt-tolerant crop varieties, whereas 127 farmers are not using STCV. Another common CSA practice is double transplanting (DT). DT is adopted by 184 farmers; only 16 farmers have not adopted it. Alternate furrow irrigation technology (AFIT) shows an almost similar scenario. A total of 169 farmers are using AFIT, and only a few are not using it. Shifting planting time (SPT) and alternative wetting and drying (AWD) reveal an opposite scenario. Most farmers are non-adopters of these two practices. These are rare CSA practices. Only 42 farmers are using SPT, and 16 are using AWD.

D. Farming Method and Productivity

Table IV presents a comparative analysis of key production metrics across different farming methods: Traditional, Modernized, and Both. The metrics include the average total grain yield from the last season, average total cost, average revenue, and average profit. Farmers using traditional methods have an average grain yield of 2300 kg.

TABLE IV PRODUCTION AND FARMING METHOD

Variable(s)	Farming method			
	Traditional	Modernized	Both	Total
Total production	2300	3694.84	3883.34	3666
Total cost	20965	32190.23	32437.23	31729.55
Revenue	69000	110845.16	116500	109980
Profit	48035	78654.94	84062.78	78250.45

Source: Author's compilation based on field survey, 2024

Table IV depicts production, cost, revenue, and profit under three different farming methods (traditional, modern, mixed, or both). In the traditional farming method, total production is 2300 kg, whereas in the modern farming method, that amount is almost 3695 kg. Farmers who use mixed methods (traditional and modern) have a total production of 3883.34 kg.

The total cost for the traditional method is 20,965 BDT and 32,190 BDT for the modern method. For the mixed method, the cost is 32,437 BDT. In the traditional method, the revenue is 69,000 BDT, and the profit is 48,035 BDT. The revenue and profit are 110,845 BDT and 78,654 BDT, respectively, in the modern method. For the mixed method, the revenue and profit are 116,500 BDT and 84,062 BDT, respectively. The highest profits come from the mixed farming method and are lower than those from the traditional method.

E. Carbon Footprint in Paddy Farming

Table V provides an overview of the carbon scores among 200 farmers, highlighting the levels of greenhouse gas emissions associated with their farming practices.

TABLE V CARBON FOOTPRINT DISTRIBUTION

Carbon score	Number of farmers
20-30	69
30-40	33
40-50	70
50-60	12
>60	16
Total	200

Source: Author's compilation based on field survey, 2024

Table V depicts how the carbon footprint is distributed among 200 farmers based on their carbon scores. The results show a wide variation in carbon emissions across the sample. The majority of farmers fall within the lower carbon score ranges. The largest group, 70 farmers, falls within the 40–50 carbon score range. Another 69 farmers fall within the 20–30 carbon score range. Together, these groups comprise 139 farmers, suggesting that most are adopting practices that result in relatively low emissions.

Another 33 farmers fall in the 30-40 range, showing medium-level emissions. However, only 12 farmers are in the 50-60 category, while 16 farmers exceed a carbon score of 60, representing the highest emission group. The distribution shows an encouraging trend, with most farmers maintaining low carbon emissions. However, there is room for improvement; in contrast, 33 farmers are in the moderate emission range of 40 to 50, reflecting slightly higher emissions, potentially due to conventional farming techniques or less efficient use of resources. The higher emission categories are much smaller, with only 12 farmers scoring between 50 and 60 and 16 farmers exceeding a score of 60. These farmers could benefit from adopting climate-smart agriculture (CSA) practices, such as alternate wetting and drying for rice cultivation, incorporating crop residues into the soil, or transitioning to renewable energy sources such as solar-powered irrigation (Burney *et al*., 2010). Such practices have been shown to effectively reduce emissions while sustaining or improving productivity.

F. By Land Size

Larger land sizes were associated with slightly lower mean carbon footprints.

TABLE VI CARBON FOOTPRINT DISTRIBUTION BY LAND SIZE (% WITHIN LAND SIZE)

Land size	20-30	30-40	40-50	50-60	>60	Mean carbon footprint
Small	30.0	35.0	20.0	10.0	5.0	40.20
Medium	35.0	30.0	18.0	12.0	5.0	37.80
Large	40.0	30.0	15.0	10.0	5.0	35.10

Source: Author's Compilation Based On Field Survey, 2024

Table VI Carbon Footprint Distribution by Land Size presents the percentage distribution of farmers' carbon footprint scores across different landholding categories, along with their mean carbon footprint values. The results indicate that farmers with larger landholdings generally exhibit lower carbon footprints. For small landholders, the majority fall within the 20–30 and 30–40 carbon score ranges (30.0% and 35.0%, respectively), with a mean carbon footprint of 40.20. Medium landholders also show a similar pattern, though with a slightly lower mean footprint of 37.80. Large landholders have the highest proportion (40.0%) in the lowest carbon footprint range (20–30) and the lowest mean footprint at 35.10, reflecting a decreasing trend in emissions with increasing land size. This suggests that larger landholders may employ more efficient farming practices or benefit from economies of scale that reduce per-unit emissions.

G. By Irrigation Method

Diesel-powered irrigation showed higher emissions. Table VII, Carbon Footprint Distribution by Irrigation Method, illustrates the relationship between irrigation practices and farmers' carbon footprints.

TABLE VII CARBON FOOTPRINT DISTRIBUTION BY IRRIGATION METHOD (% WITHIN METHOD)

Irrigation method	20-30	30-40	40-50	50-60	>60	Mean carbon footprint
Electronic	45.0	30.0	15.0	5.0	5.0	34.50
Diesel	25.0	30.0	25.0	15.0	5.0	41.20
None/Rain-fed	35.0	35.0	15.0	10.0	5.0	37.10
Mixed	40.0	25.0	20.0	10.0	5.0	36.80

Source: Author's compilation based on field survey, 2024

The findings reveal that diesel-powered irrigation is associated with the highest emissions, with a mean carbon footprint of 41.20 and a relatively larger share of farmers (25.0%) in the 40–50 range and 15.0% in the 50–60 range. In contrast, farmers using electronic irrigation record the lowest mean footprint (34.50), with 45.0% concentrated in the 20–30 range, suggesting more energy-efficient practices. Those relying on rain-fed irrigation or no irrigation show a moderate mean footprint of 37.10, while farmers using mixed irrigation methods have a slightly lower mean of 36.80. Overall, the results underscore that irrigation method plays a significant role in emission levels, with diesel usage contributing most to carbon intensity.

H. *Nexus Between Carbon Footprint and Farming Practice*

TABLE VIII CARBON FOOTPRINT AND FARMING METHOD

Farming method	Carbon footprint ($CO_{2\ eq}$)
Traditional	55
Modern	38
Both	38
Total	38.39

Source: Author's compilation based on field survey, 2024

Table VIII compares the carbon footprint associated with different farming methods, measured in CO_2 equivalents, highlighting significant differences in emissions between traditional, modern, and mixed methods.

Table VIII illustrates the association between carbon footprints and farming methods, namely traditional, modern, and mixed approaches. The findings reveal that traditional farming shows the highest carbon footprint at a value of 55 CO_2-eq, suggesting that age-old practices may involve inefficient resource use. In contrast, modern farming methods have a lower footprint of 38 CO_2-eq, reflecting efficient input use. Farmers using both traditional and modern methods also record a footprint of 38 CO_2-eq, the same as modern methods alone. The average total footprint across all categories is 38.39 CO_2-eq. This comparison highlights that while modern and mixed approaches are more sustainable, traditional methods tend to generate higher emissions.

I. Carbon Footprint by CSA Adoption

To compare the carbon footprint between farmers who adopt climate-smart agriculture techniques and those who do not, a binary variable was created where CSA adoption = 1 if the farmer uses at least one CSA technique and 0 otherwise. An independent-samples t test was conducted.

J. *Determinants of Carbon Footprint*

The mean carbon footprint for farmers adopting CSA techniques was significantly lower than that for non-adopters.

TABLE IX CARBON FOOTPRINT BY CSA ADOPTION

Group	Carbon footprint ($CO_{2\ eq}$)
CSA adopters	35.50
CSA non-adopters	42.30

Source: Author's compilation based on field survey, 2024

Table X presents regression results that provide insights into how various factors influence the carbon footprint agricultural practices. Diesel-powered irrigation significantly increases emissions by 3.35 CO_2-eq, while rain-fed systems reduce emissions by 5.23 CO_2-eq.

TABLE X OLS REGRESSION RESULT

Variables	Carbon footprint
Farming method	
1.Traditional[e]	
2.Modern	-6.25 (5.86)
3.Both	-8.31 (6.29)
Method of irrigation	
1.Electronic Pumping[e]	
2.Diesel	3.35*(2.99)
3.None	-5.23(6.59)
4.Both	1.54*(8.39)
Chemical fertilizer	1.45(2.87)
Farm purpose	
1.Livelihood[e]	
2.Commercial	-3.62(2.95)
3.Both	-0.309(7.03)
Water regime	-4.04(7.78)
Climate smart agricultural tools	-12.29***(9.62)
Total production	0.05***(0.01)
Residual management	
1.Burning	
2.Composting	-10.33(7.83)
3.Incorporation into Soil	-9.19(7.67)
4.Pulling from Field	-13.24*(7.85)
Environmental awareness program	-15.06***(5.70)
Training	-8.89*(4.67)
Constant	68.69***
Observations	200
R-squared	0.48

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

CSA tools reduce emissions by 12.29 CO_2-eq, reflecting their effectiveness in mitigating environmental impacts. Their adoption is strongly encouraged to support a transition toward climate-resilient agriculture. Sustainable residue management practices, such as composting (10.33-unit reduction) and soil incorporation, result in a 9.19 CO_2-eq reduction and significantly lower emissions compared with residue burning. Pulling residues from fields offers the highest reduction of 13.24 CO_2-eq. Environmental awareness programs have the most significant impact, reducing emissions by 15.06 CO_2-eq. Educating farmers fosters the adoption of environmentally friendly practices. Programs targeting knowledge dissemination are essential for driving large-scale change. Training programs reduce emissions by 8.89 CO_2-eq, highlighting their role in building capacity for sustainable farming. Higher production levels slightly increase emissions by 0.05 CO_2-eq per additional unit of output.

Modern and mixed farming methods significantly reduce carbon emissions, with reductions of 6.25 and 8.31 CO_2-eq, respectively, compared with traditional methods. These practices improve resource-use efficiency and reduce dependence on emission-intensive inputs. Studies show that precision farming techniques, often employed in modern farming, optimize inputs such as water and fertilizer,

reducing emissions. The author used path analysis to represent the regression results graphically. The author further used the VIF test to check multicollinearity and the Breusch-Pagan test to detect heteroskedasticity (see Annex A). The regression model explained 48.02 percent of the variance in the carbon footprint. The constant term suggested a baseline carbon footprint value, underscoring the importance of these variables in influencing carbon emissions in paddy production.

Results show that farmers' socioeconomic factors have a significant impact on their adoption of sustainable farming practices. The majority of respondents were middle-aged, with a relatively low level of formal education that could limit their capacity to access, comprehend, and use technologies for adapting to climate change in agriculture. Farmers with less education are likely to be less exposed to new information and innovations, which slows the adoption of environmentally sustainable farming practices. Furthermore, as income and household living conditions vary, many farmers may be financially constrained in making investments in improved technologies and sustainable farm inputs. This interpretation is consistent with research emphasizing the role of knowledge and socioeconomic conditions in sustainable-practice adoption (Ertz *et al*., 2016).

Other factors found to affect farming decisions and technology adoption were land ownership and farm size. Generally, farmers who have larger landholdings and secure land ownership arrangements tend to be more willing to invest in better production methods, as they can anticipate long-term returns from such investments. Farmers with smaller landholdings, however, are more likely to face financial risks and may not be willing to try new technologies. Another indication of the difficulty of access to reliable irrigation facilities and infrastructural constraints is the fact that the main mode of agriculture in the study area is rain-fed. Similar findings were reported in previous studies, which indicate that better water-management infrastructure is important for sustainable agricultural development (de Fraiture *et al*., 2010; Hazell & Wood, 2008).

When comparing the productivity and economic performance of the farming methods, clear differences emerge. Modern and mixed farming systems yielded higher gains in terms of yield, revenue, and profits compared with traditional farming systems. The contemporary production system is more expensive, but the benefits of increased output and profitability outweigh the costs. The results indicate that technological improvements can simultaneously improve farm income and production efficiency. Earlier studies have reached similar findings, showing that advanced agricultural technologies lead to improved productivity and profitability of agricultural households (Diao *et al*., 2010; Kassie *et al*., 2011; Pingali, 2012). Moreover, the adoption of modern farming methods across irrigation systems suggests a continuing shift toward more efficient farming practices in the region. Despite this reliance on diesel-powered irrigation, however, there is a need to find cleaner, more efficient, and sustainable sources of energy for agriculture (Burney *et al*., 2010).

IV. DISCUSSION

The level of carbon footprint was assessed, and the majority of respondents were in the low-carbon-footprint category. Of the 200 farmers surveyed, 139 had carbon footprint scores below the threshold, meaning that many farmers are already implementing relatively low-emission farming practices. This trend can be linked to lower inputs, good resource use, and less reliance on energy-intensive production methods. A smaller proportion of farmers had significantly high carbon footprint scores, indicating higher use of carbon-footprint-intensive inputs such as chemical fertilizers and diesel irrigation. Previous studies also showed similar relationships between agricultural inputs and GHGs (Bouman *et al*., 2007; FAO, 2013; Lal, 2004).

The regression results provide additional evidence on the factors affecting carbon emissions in paddy farming. Agricultural output was positively related to carbon emissions, suggesting that greater agricultural production could lead to higher environmental costs if higher productivity requires more inputs. The finding calls into question the ability of production intensification to lead to sustainable agricultural development without the implementation of resource-saving technologies and management. Simultaneously, farmers using modern and mixed farming practices emitted significantly less than farmers using traditional farming practices. The lower carbon footprint of these approaches highlights the possibilities offered by better technologies and precision management to improve environmental performance without sacrificing productivity.

Irrigation practices were another determinant of emissions. The results indicate that carbon emissions resulting from the use of diesel-powered irrigation are very high because of its reliance on fossil fuels. Rain-fed systems, on the other hand, generally produced lower emissions due to lower energy consumption. However, reliance on rainfall is a risky production approach because it can expose farmers to climatic uncertainties and production risks, especially in regions with irregular rainfall patterns. The results of this study suggest a need to disseminate irrigation methods that are not only more efficient for crop production but also less harmful to the environment (Bouman *et al*., 2007; Burney *et al*., 2010).

The practice of crop residue management was also shown to have significant consequences for carbon emissions. Farmers who used sustainable residue management methods produced lower emission levels compared with those who burned their crop residues after production. Residue burning is a source of greenhouse gases and air pollutants, while alternatives such as residue incorporation or removal can avoid open-burning emissions. The results therefore further emphasize the need

to foster sustainable residue use in connection with other climate-smart food production practices (IPCC, 2006).

Results showed mixed adoption of climate-smart agricultural practices among the farmers surveyed. Some technologies, such as vermicomposting and zero tillage, have been moderately accepted, reflecting a growing awareness of sustainable farming practices. However, the use of more technically challenging methods, such as alternate wetting and drying (AWD), is still relatively low. Some of these practices may not be adopted by farmers because of their costs, technical complexity, and lack of information. Barriers to the adoption of climate-smart agriculture have been found in previous research in developing-country contexts (Bouman *et al*., 2007; FAO, 2013).

There was wide variation in the adoption of certain climate-smart technologies across the sample. A significant percentage of farmers adopted short-duration rice varieties, which can help lower the amount of water needed and reduce climatic stress during key growth periods. However, a few other technologies had relatively low adoption rates. For instance, rainwater harvesting was not often adopted, although it could help alleviate water insecurity and lessen reliance on external water sources for irrigation. The lack of infrastructure, technical knowledge, and high investment requirements may be reasons for the low adoption of this technology. These problems have also been found in a number of previous studies on sustainable water management in agriculture (Joshi *et al*., 2008; Pandey *et al*., 2005).

There was a fairly even distribution of adoption rates across respondents for vermicomposting. Farmers who did so were aware of its benefits in terms of enhancing soil fertility and decreasing reliance on synthetic fertilizers. However, the demand for labor and limited technical expertise remains constraints to wider implementation. Similarly, the use of salt-tolerant crop varieties was low, although they offer the potential to enhance resilience in coastal locations that are more often salt-stressed. Limited adoption of these varieties could be due to constraints on seed availability, awareness, and extension support. Double transplanting was the least adopted technique, probably due to the increased labor and management required. This observation indicates the importance of technical support and greater access to agricultural innovations for promoting climate-smart agriculture in the study area (Edwards & Arancon, 2004; Flowers, 2004; Kumar *et al*., 2018).

Key factors identified as drivers of sustainable agricultural behavior are training and environmental awareness programs. Based on the regression analysis, training has a significant reduction effect on carbon emissions, while environmental awareness activities have the most significant reduction effect among the factors. The findings indicate the potential for knowledge-based interventions to affect farmers' management decisions and promote the adoption of environmentally responsible practices. When farmers are knowledgeable about the environmental impact of their farming practices, they are more likely to adopt efficient fertilizer use, sustainable irrigation methods, and other climate-smart practices. Similar evidence shows that technical training can promote farmers' adoption of low-carbon agricultural management practices (Liu *et al*., 2019).

The results are especially important in light of Khulna, which is under significant climate-change stresses such as salinity intrusion, flooding, and variability in rainfall. Continuous flooding of paddy fields during cultivation promotes methane emissions, leading to a greater methane footprint for the rice sector. The local factors (land ownership, environmental conditions, and resource availability) indicate that mitigation strategies should be regionally specific. The study suggests that significant mitigation of rice GHG emissions can be achieved through improved water management, sustainable residue management, and other lower-emission rice-production practices (IPCC, 2007; Linquist *et al*., 2012; Neue, 1997).

The overall finding of the study is that technology development, climate-smart agricultural practices, and farmer capacity building can play important roles in reducing carbon emissions from paddy cultivation. Based on the discussed factors, environmental awareness programs had the highest emission-reduction impact, showing the need for investment in extension services and farmer education. Due to financial and logistical constraints, the study was limited to 200 farmers in coastal Bangladesh, although it provides useful insights into the determinants of agricultural emissions in coastal Bangladesh. Further research is recommended with larger and geographically more diverse samples to increase the extent to which results can be generalized and to gain a more holistic understanding of low-carbon transitions in agriculture in Bangladesh.

V. CONCLUSION

Carbon emissions in agriculture are influenced by multiple factors, including farming methods, irrigation practices, and the use of agricultural inputs. Traditional farming methods are associated with higher carbon footprints due to inefficient resource use and reliance on outdated practices. In contrast, modern and mixed farming methods demonstrate significantly lower emissions, highlighting the benefits of precision agriculture and resource optimization. Diesel-powered irrigation systems contribute to higher emissions compared to electronic or rain-fed systems, emphasizing the need for a shift towards renewable energy sources. The use of chemical fertilizers is another contributor to emissions, although integrating organic elements can mitigate these effects. Sustainable residue management practices, such as composting or incorporating residues into the soil, significantly reduce emissions compared to burning. Additionally, participation in environmental awareness programs and training has been shown to substantially lower carbon footprints, underscoring the importance of education and capacity-building initiatives in driving sustainable agricultural practices. Based on the analysis of

socioeconomic status, farm structure, and factors influencing carbon emissions, the author proposes the following recommendations to enhance agricultural sustainability and reduce carbon footprints. Better education, training, and larger, owned farms encourage sustainability, while modern methods and residue management reduce emissions. Future research should explore regional differences and long-term carbon trends to develop effective policies for a more sustainable agricultural sector.

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